# Heavy ion mass loading of the geomagnetic field near the plasmapause and ULF wave implications

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[1] The structure of the density discontinuity across the plasmapause is often based on electron and $H^+$ density profiles with the contribution of heavy ions ($He^+$, $O^+$ etc) neglected. Electron and ion density measurements in this region may differ significantly due to the presence of heavy ions and it is important for the intercomparison of different datasets to understand these differences. Dynamics Explorer (DE-1) magnetic field and plasma composition data have been used to compare heavy ion responses across the plasmapause and to calculate the mass loaded ion density ($\rho$) profiles. To illustrate this we investigate mass loading through radial profile variations in the Alfven velocity ($V_A$). Results show that the gradient in $\rho$ and $V_A$ across the plasmapause is modified when mass loading due to multiple heavy ion species is included, particularly in the presence of the $O^+$ torus. Application to ultra-low frequency (ULF) field line resonance is used as an example where the contribution from heavy ions smoothes out the expected ULF wave resonant frequency discontinuity at the plasmapause.
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## 1. Introduction

[2] Properties of the cold plasma in the Earth's magnetosphere divide the cavity into two distinct regions, the plasmasphere and the plasmatrough. In the high-density plasmasphere inner region ($10^2$–$10^4$ $cm^{-3}$) with its outer boundary at the plasmapause ($L$ = 3–5), geomagnetic flux tube trajectories corotate with the Earth under the influence of the corotation electric field creating a closed region [*Nishida*, 1966]. Flux tube trajectories further out are dominated by the magnetospheric convection electric field and intersect the dayside magnetopause. These flux tubes become open at the magnetopause and the plasmatrough flux tubes have low density (1–10 $cm^{-3}$). The plasmapause ideally supports a zero electric field singular point at 1800 LT and the plasmapause bulge region between noon and midnight, depending on geomagnetic activity and convection. The plasmapause density gradient can be very steep at most local times, with the exception of the bulge region in the dusk sector which may show more gradual slope and multiple plasmaspheric structures [*Horwitz et al.*, 1990; *Carpenter et al.*, 2000]. Convection in the plasmatrough is unsteady, mainly due to substorm activity. When convection decreases the corotating flux tubes are extended beyond the plasmapause and the new corotating tubes are refilled with plasma of ionospheric origin. Also, tails or plumes may drift sunward from the plasmapause towards noon and provide density enhancements in the plasmatrough [*Chappell et al.*, 1971; *Carpenter et al.*, 1993]. Consequently, the radial plasma density profile in the magnetosphere, including the plasmapause, may show considerable variability [*Horwitz et al.*, 1990; *Singh and Horwitz*, 1992; *Carpenter et al.*, 2000]. Results from the IMAGE spacecraft have provided more insight into the azimuthal topology of the plasmasphere and the plasmapause. For example, the Extreme Ultra-Violet (EUV) instrument has recently confirmed the existence of plasma tails, fingers, biteouts and shoulders [*Sandel et al.*, 2001].

[3] The radial ion plasma density profile, typically used to display the presence of the plasmapause, is generally deduced from electron or $H^+$ ion measurements [*Carpenter and Anderson*, 1992; *Chappell et al.*, 1970]. Recently the dynamics of the plasmapause have been studied using the IMAGE EUV instrument which indirectly measures the total column density of $He^+$ ions [*Burch et al.*, 2001]. It is important to intercompare these different measurements in order to define their response at the plasmapause and in the plasmasphere. Ion composition measurements have shown $He^+$ is the second most abundant ion in the plasmasphere, after $H^+$, with an average relative concentration of 20%, but is sometimes comparable to that of $H^+$ [*Newberry et al.*, 1989]. Just inside the plasmapause heavy ion ($O^+$, $O^{++}$ and $N^+$) densities have been found to increase by a factor of 10 or more when there is no corresponding variation in $H^+$ or $He^+$ ions. This is commonly called the oxygen torus due to the dominance of oxygen ions [*Roberts et al.*, 1987]. *Horwitz et al.* [1984] showed that the ion composition in the plasmasphere and near the plasmapause is highly variable and typically includes $H^+$, $He^+$, $He^{++}$, $O^+$ and $O^{++}$ ions. Therefore, mass loading will vary radially and the assumption of a constant mass loading, as assumed by *Moore et al.* [1987] and *Fraser et al.* [1988] and others in the past, is not appropriate. In this paper the plasmapause is identified as a sharp radial gradient in the $H^+$ density profile.

[4] A wide variety of hydromagnetic waves propagate in the Earth's plasmasphere and magnetosphere. Spacecraft observations on the dayside of toroidal mode standing Alfven waves show a decrease in field line resonant frequencies with increasing radial distance from the Earth, and the presence of harmonic structure over $L$ = 3–9

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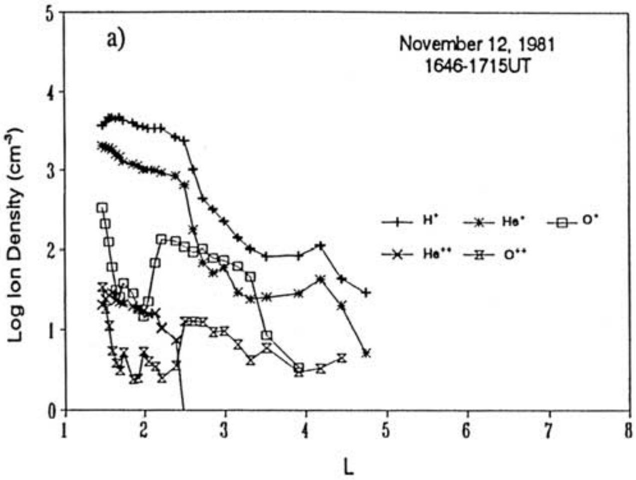


**Figure 1a.** Radial variation in ion density of five species on one DE-1 inbound pass on November 12, 1981.

[*Engebretson et al.*, 1986; *Takahashi and Anderson*, 1992]. The extent to which plasma mass density near the plasmapause affects ULF field line resonance characteristics is not understood. The approximate wave resonant frequency and harmonics can be simply calculated by integration along a field line using $T = 1/f \sim \int (V_A)^{-1} ds$ where the Alfven velocity $V_A = B(s)[(\mu_o \rho(s)]^{-1/2}$ is the characteristic wave velocity and is dependent on the plasma mass density and the geomagnetic field flux density along the field line (s). Consideration of the radial variation in $V_A$ can therefore provide insight into the resonant structure of the magnetosphere. The populations of cool/cold heavy ions ($He^+$, $O^+$) in addition to protons and electrons introduces a mass loading factor to the plasma ion density since $\rho = \Sigma m_i n_i$, where $m_i$ and $n_i$ are the mass and number density respectively, of the ith ion species.

[5] The primary aim of this paper is to include heavy ion contributions in the radial mass loaded plasma density profile and show an example of the resulting $\rho$ and $V_A$ profiles. Data is from the Dynamics Explorer (DE-1) spacecraft, in a near polar orbit with 7.5hr period, apogee 4.65Re and perigee 570 km. Plasma data is from the retarding ion mass spectrometer (RIMS) experiment [*Chappell et al.*, 1981] and geomagnetic field data from the magnetic field experiment [*Farthing et al.*, 1981]. As an example illustrating the importance of ion composition and mass loading, the resulting $V_A$ profiles are then incorporated in calculations of ULF wave field line resonance harmonic structure following techniques used by *Orr and Webb* [1975] and *Fraser et al.* [1988].

## 2. Plasma Density, Mass Loading, and Alfven Velocity Profiles

[6] An important study on the replenishment of the outer plasmasphere following a geomagnetic storm using DE-1 cold multi-ion plasma density profiles was reported by *Horwitz et al.* [1984]. A sequence of five consecutive DE-1 dusk passes on 12, 13 November 1981, were shown where magnetic activity decreased gradually from $K_p = 7$ at 03–06 UT on 12 November to $K_p = 0$–$1$ at 18 UT on 13 November. During the period of quieting, the region outside $L \sim 4$ extending to $L \sim 7$ began to refill and a new outer plasmasphere formed. An enhanced $O^+$ population comparable to $H^+$ was also observed.

[7] In the present study we use the DE-1 RIMS multi-ion density data for one of the passes on 12 November 1981, between 1646–1715 UT, along with the corresponding measured geomagnetic field, to calculate the $V_A$ profile and field line resonance harmonic structure over $L = 1.5$–$5$. Here DE-1, over 1924–1948 LT, was located at 0.4°–43.6° geomagnetic latitude and at an altitude of 1.5–2.4 Re. The radial density profiles of the five species $H^+$, $He^+$, $He^{++}$, $O^+$ and $O^{++}$ are plotted in panel C of Figure 2 by *Horwitz et al.* [1984]. This panel is reproduced here in Figure 1a, where the intrusion of new cold plasma during plasmasphere refilling is seen in $H^+$ and $He^+$ densities over $L = 2.5$–$4$. In this region $O^+$ is enhanced to an extent that it sometimes exceeds the $H^+$ density. This is the so-called heavy ion "torus" or "shell" in the vicinity of the plasmapause [*Roberts et al.*, 1987; *Singh and Horwitz*, 1992]. Errors in density may be a factor of two for densities <100 $cm^{-3}$ and are not considered. Figure 1b shows mass loaded density profiles for the two component ($H^+$, $He^+$) and three component ($H^+$, $He^+$, $O^+$) plasmas, with the single ion $H^+$ profile plotted for comparison. The inclusion of $He^+$ doubles the density over $L = 3$–$4$ while the further addition of $O^+$ increases it by over one order of magnitude and essentially eliminates the plasmapause at $L \sim 2.5$. $V_A$ profiles, calculated from the multi-ion mass loaded plasma density profiles in Figure 1b and the corresponding DE-1 magnetic field radial profile data are plotted in Figure 2. The shape of the $V_A$ profiles for the ($H^+$, $He^+$) and ($H^+$, $He^+$, $O^+$) density profiles are significantly different with the latter showing an order of magnitude decrease over $L \sim 2$–$4.5$, primarily due to the mass loading of the $O^+$ torus ions.

## 3. Field Line Resonance

[8] The increase in mass loading resulting from the presence of significant populations of $He^+$ and $O^+$ ions has a profound effect on the ULF wave field line resonance (FLR) harmonic structure, as shown in Figure 3. Here the eigenfrequencies of the first three harmonics were computed

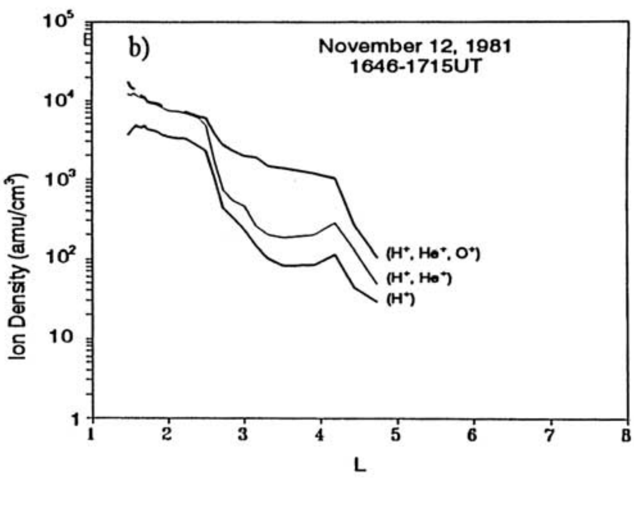


**Figure 1b.** Mass loaded ion densities for two combination of ion species compared with the $H^+$ density.

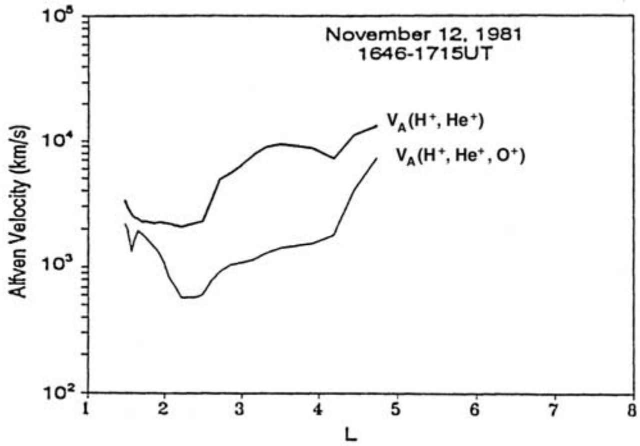


**Figure 2.** Radial Alfven velocity profile for the ion combinations of ($H^+$, $He^+$) and ($H^+$, $He^+$, $O^+$).

following the techniques of *Cummings et al.* [1969] and *Orr and Matthew* [1971]. A dipole magnetic field and a magnetosphere plasma density power law variation $\rho = \rho_o (R_e)^{-m}$ with m = 3, are assumed [*Fraser et al.*, 1988]. For the ($H^+$, $He^+$) plasma, the expected decrease in resonant frequency with increasing radial distance is seen out to $L \sim 2.5$. The presence of the plasmapause prior to refilling at this location, and the decrease in density of the $H^+$ and $He^+$ ions out to $L \sim 4$ creates a region of increased FLR frequencies. For example, the fundamental frequency of 15 mHz at $L$ = 2.5, increases to 40 mHz at $L$ = 3.3. The second and third harmonics increase proportionally (Figure 3a). The inclusion of $O^+$ in the computation almost completely suppresses the increase in resonance frequency across the plasmapause (Figure 3b). A significant frequency increase occurs beyond $L$ = 4 where the $O^+$ density decreases. Throughout the study the contributions of $He^{++}$ and $O^{++}$ ions have been neglected.

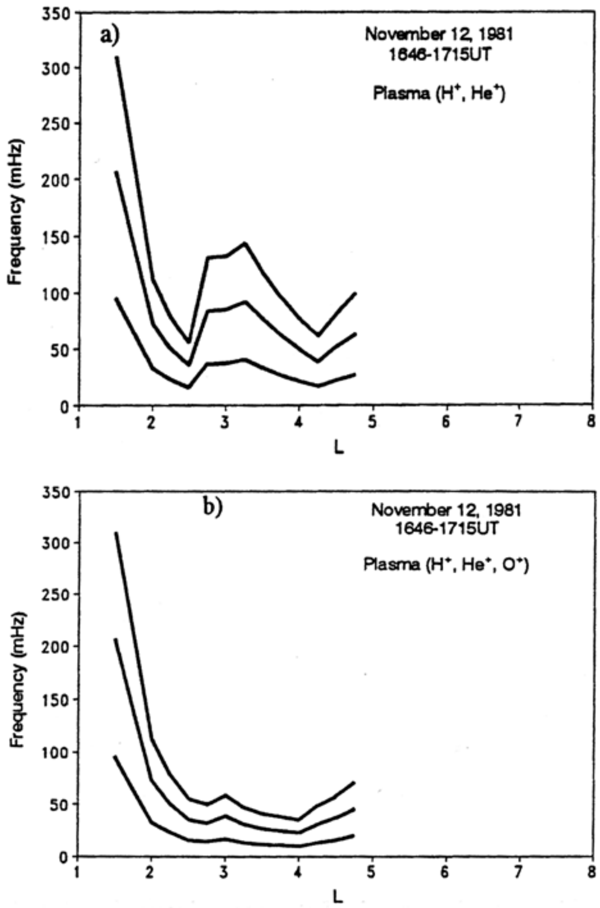


**Figure 3.** Field line resonance eigenfrequencies for the first three harmonics, computed using mass loading with, (a) $H^+$ and $He^+$ ions, and (b) with $H^+$, $He^+$, and $O^+$ ions.

## 4. Discussion

[9] The above example shows that the $H^+$ radial plasma density profile cannot always be assumed representative of the total ion density profile, especially near the plasmapause. The same argument may apply to the use of electron density profiles. An example highlighting this effect was presented by Z. C. Dent et al. (Plasmaspheric depletion, refilling and plasmapause dynamics: A coordinated ground-based and IMAGE satellite study, submitted to *Journal of Geophysical Research*, 2005; hereinafter referred to as Dent et al., submitted manuscript, 2005) assuming a dipole magnetic field and a radial m = 3 plasma density distribution. Plasma mass density, calculated from ULF field line resonance frequencies determined from SAMNET [*Yeoman et al.*, 1990], IMAGE [*Lühr et al.*, 1998] and British Geological Survey [*BGS*; http://www.dcs.lancs.ac.uk/iono/samnet/] ground-based magnetometer observations using the cross-phase technique [*Waters et al.*, 1991] were compared to in-situ IMAGE satellite Radio Plasma Imager (RPI) determined electron number density values. In Figure 4 the cross-phase determined plasma mass density profile has a less steep plasmapause gradient than the sharp RPI determined electron number density profile at $L \sim 3$. This day, 14 May 2001, followed a depletion episode and Dent et al. inferred that the differing profiles through the plasmatrough region resulted from an enhanced heavy ion population. There was an excellent ground-satellite conjunction during this interval with the two data sets representing the same UT

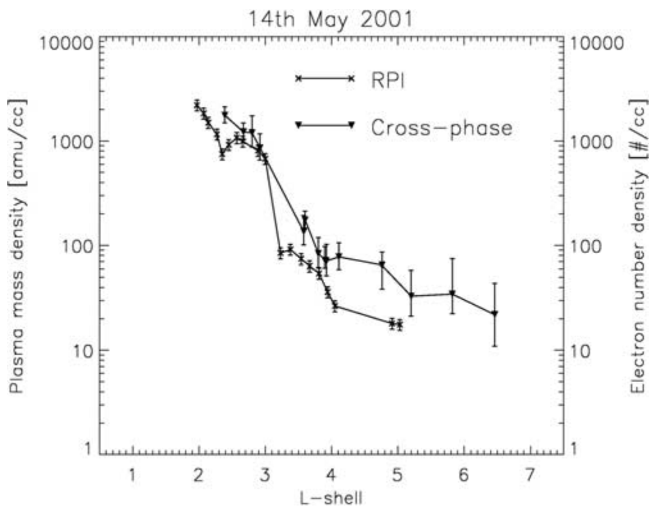


**Figure 4.** Cross-phase determined equatorial plane plasma mass density profile and in-situ IMAGE RPI electron number density profile. (Reproduced from part of Dent et al. (submitted manuscript, 2005).)

interval, 0817–0911 UT, and being separated in MLT by less than 30 minutes. Consequently, azimuthal variation of plasma density is an unlikely explanation for the observed differences in electron (RPI) and total mass density profiles at the plasmapause. The observed (using the cross-phase technique) FLR frequency profile, and that calculated from the RPI data assuming a $H^+$ plasma and using the same method as in the above section (not shown), shows a suppressed increase of frequency through the plasmapause when heavy ions are accounted for (i.e., in the cross-phase profile) as compared to when they are not (i.e., the RPI profile), in agreement with the results presented in Figure 3.

[10] This application illustrates the importance of choosing the relevant plasma density profile for the particular application under study. The electron density profiles derived from upper hybrid resonances on numerous spacecraft [e.g., *Anderson et al.*, 1992] are important in VLF studies involving electron cyclotron waves. On the other hand ULF hydomagnetic and ion cyclotron waves propagate in an ambient ion plasma usually dominated by $H^+$ ions, but with a significant contribution from heavy ions including $He^+$ and $O^+$. The use of electron density in propagation and resonance studies of these waves is therefore invalid with the exception of the special case where heavy ions are absent.

[11] The DE-1 pass reported here is only one example of 8 passes observed in the DE-1 data set over October–November 1981 which showed significant heavy ion mass loading effects. Results from these observations on different days over a wide range of magnetic conditions suggest that $V_A$ will show the expected increase at the plasmapause and the corresponding decrease in ULF wave frequency. If a steep plasmapause is observed in the $H^+$ and $He^+$ ions, and the $O^+$ contribution is minimal, as shown in Figure 1b, then resonant structures similar to Figure 3a, with a sudden frequency increase at the plasmapause will be observed. However, the presence of an $O^+$ torus may flatten the $V_A$ profile at the plasmapause due to $O^+$ refilling and remove this frequency increase.

[12] In conclusion, this preliminary study emphasizes the importance of heavy ion mass loading in plasmapause and plasmasphere density studies. With respect to hydromagnetic waves it is important to use mass loaded densities in order to locate the plasmapause accurately and calculate meaningful FLR radial frequency profiles in the plasmasphere. Here the mass density profile may be significantly different from that indicated by the electron or $H^+$ density profile. With the wide variety of plasmaspheric and magnetospheric spacecraft plasma density data currently available it is important to use the appropriate data for the application under study and undertake inter-comparisons with care.

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